SOLAR RESEARCH AT THE MOUNT WILSON OBSERVATORY

By Ferdinand Ellerman

The activity of the Sun during the present sun-spot period, which reached its maximum about August, 1917, has offered many opportunities for observing and recording exceptional phenomena in the regions occupied by sun-spots. Some of the observations have been made and recorded visually, but the majority are photographic.

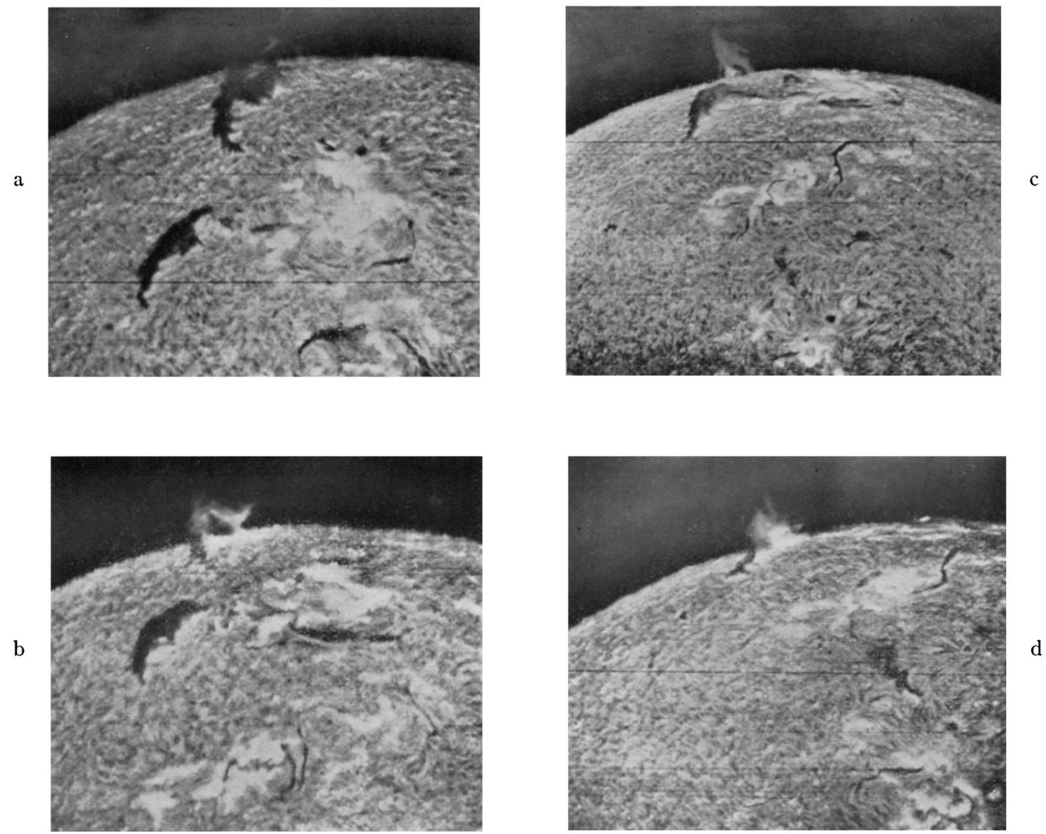
The instruments employed in the solar work during the last three years are the two tower telescopes. The Snow horizontal telescope has been dismantled and remodeled, but owing to the activities of our instrument shops in turning out war work for the government during the past two years the completion of the changes in the spectroscopic equipment for this telescope has been temporarily deferred.

The 60-foot Tower Telescope

The 5-foot spectroheliograph, which had been used in the Snow telescope since October, 1905, was transferred to the 60-foot tower telescope in December, 1915, where it is used to record the $H\alpha$ hydrogen flocculi on the 6.5-inch solar image formed by the 60-foot objective. It is mounted on beams overhead, in the observing room, and by means of a countershaft it is driven across the Sun's image by a variable speed motor, which also drives the 13-foot spectroheliograph described below. By rolling into place a diagonal mirror mounted on a carriage which runs on rails above the 13-foot spectroheliograph, the Sun's image is reflected on to the slit of the 5-foot spectroheliograph.

A grating having a very brilliant first-order spectrum is used for the dispersion. The light from the slit, after passing thru the collimating lens, is reflected by two plane mirrors on to the grating, which is turned so that the normal reflection is thrown beyond the camera lens. This makes the angle of incidence very large, resulting in a magnification of the spectrum scale, so that at $H\alpha$ 1^{mm} equals about 4.5 A, which is more than twice the normal scale of dispersion and is sufficient to isolate the line from the continuous spectrum by means of the second slit.

PLATE II



Western part of the Sun photographed on (a) June 27, (b) June 28, (c) June 29, and (d) June 30, 1917, illustrating how dark hydrogen prominences projected on the disk become bright prominences at the limb of the Sun.

The small angular aperture, however, combined with the slowness of red sensitive plates of strong contrast, would make the exposure time prohibitive in making a run across the 6.5-inch image were the center of the line employed. The slit is therefore opened to include the entire line and its edges. This is sufficient to show the general distribution of the hydrogen flocculi, both bright and dark, over the Sun's surface, the lower level structure, and also the main features of the higher levels, including prominences projected on the disk. The width of the first slit is 0.15^{mm}, and that of the second is 0.20^{mm}, and the time of exposure-run about 20 minutes.

All the other photographs of flocculi and prominences are made with the 13-foot spectroheliograph. This instrument consists of a heavy box made of 12-inch channel iron, running horizontally on four large steel ball bearings, and moved across the Sun's image by means of a screw, driven by the variable speed motor and countershaft mentioned above, and a worm gear reduction. On the top of the box are mounted the first slit and two second slits, A and B. On the under side, extending into the 30-foot well, is an angle-iron frame, carrying the platform on which are mounted both the casting supporting the 13-foot collimator and camera lenses and mirror, and the casting for the grating support. The grating is similar to the one in the 5-foot spectroheliograph, and with the 13-foot focus lens gives a dispersion of 3.5 A per mm. at Hα. With this instrument, which has been in use since July, 1915, about 4500 plates have been made.

The slit widths employed for the spectroheliograms of the Sun's disk are 0.10^{mm} for the first slit, and 0.15^{mm} for the second when using the Hα or K2 line. When photographing the prominences, both the first and second slits are opened to 0.40^{mm} to admit sufficient light. Two second slits are employed when the surface of the Sun is being photographed. One is set on the center of the spectrum line used and the other on the continuous spectrum, thereby obtaining two simultaneous images on the plate, one showing the flocculi and the other the spots as in a direct photoheliogram. This gives a means of direct comparison without distortion between the two images.

Two objectives are employed, one a 12-inch visual of sixty feet focal length, the other a 4-inch photographic of eighteen feet focus The latter gives a 2-inch image of the Sun.

As mentioned above, the larger image is used for the work with the 5-foot spectroheliograph for daily photoheliograms, and with the 13-foot for detail work on the Sun's surface and prominences. The 2-inch image is used to record the general distribution of the hydrogen and calcium flocculi and the prominences. Two exposures are usually made on each plate when the small image is used, varying the speed so as to get a duplicate record with different density.

The plates used are Wratten M for exposures with Hα, Seed 23 for K calcium prominences, and Seed Process O for K_2 calcium flocculi and for photoheliograms.

In using the 60-foot visual objective for photoheliograms, the aperture is reduced to 2.5 inches, thereby increasing the depth of focus. On account of the form of the color curve, the plate is placed about four inches beyond the visual focus. The plates obtained in this way seem fully as good as if a photographic objective were employed.

In Plate I is shown a photoheliogram made on August 12, 1917, and also for comparison a spectroheliogram made with the 5-foot spectroheliograph, using the Hα line. It is interesting to note the considerable amount of bright hydrogen structure around the spots, covering a large part of their area and giving an entirely different appearance from that of the direct image. The large dark patches are prominences seen in projection on the disk, and record themselves by the increase in absorption of the Hα line as the slit passes across them. The bright areas likewise show a reversal or brightening of the line over these regions. In some extreme cases the reversal of Hα is much brighter than the adjacent continuous spectrum.

When in 1903 at the Yerkes Observatory we first began using the hydrogen line Hβ for spectroheliograms, we found these large dark areas on our plates, and, assuming that they were prominences seen in projection on the disk, we called them such. The objection was raised by some observers that these were not prominences seen in projection, but another phenomenon which they called filaments. Subsequently, with the 5-foot spectroheliograph in the Snow telescope, in 1908, and, especially, later with the 13-foot spectroheliograph, we showed beyond question the true nature of the objects. If there is any doubt in the mind of anyone as to the dark patches being prominences projected on the disk, he will need

only to study Plate II, which shows the western part of the Sun on June 27, 28, 29 and 30, 1917, taken with the center of the Hα line. This illustrates how these dark patches become prominences at the limb as they are carried over by the solar rotation.

The 150-foot Tower Telescope

The 150-foot tower telescope has been used entirely for spectroscopic work, both visual and photographic. The 75-foot spectrograph top was originally designed so that it could be used as a spectroheliograph, but it was found by experience that the exposure time was prohibitive because of the small angular aperture (1 to 150). The instrument has therefore been employed on the class of work for which it is so eminently suited, i. e., large scale spectra for determining (a) the existence of the general magnetic field of the Sun as well as the localized magnetic regions around sun-spots, (b) solar rotation by means of the displacement of the spectral lines, (c) motions of the vapors in sun-spots, and various other kinds of work where a large solar image and high dispersion are essential.

The earlier work was in a large measure experimental, but regular lines of work were soon determined upon. One especially, that of studying the magnetic field in sun-spots, was of prime importance, and has been prosecuted continuously since the completion of the instrument.

The daily observations begin by orienting the spectrograph top to correspond with that of the solar disk. This is projected on a screen, which has a circle with meridians and parallels of latitude marked corresponding to the date of observation, in order to determine the latitude and longitude of the sun-spots. Near the edge of the screen where the latitudes 0°, 10° and 20°, north and south, cut the circle, pin holes are punched thru the card, and the light passing thru these falls on to a paper pad 10 x 20 inches in size about four inches below. Pencil marks are made where these light patches strike and also one at the center of the disk; the screen is then swung to one side and a circle described on the paper pad corresponding to the Sun's disk. The spots are now sketched carefully, and their latitudes and longitudes noted on the sketch. The paper pad is then removed and the analyzer placed over the slit.

The analyzer consists of a long Nicol prism, with normal surfaces, built up of four sections each about 33^{mm} long, 10^{mm} wide, and 18^{mm} thick. This is mounted about one-fourth inch above the slit. Above the Nicol, between two strips of plane parallel glass, are mounted strips of mica 2^{mm} wide with their axes inclined $+45°$ or $-45°$ to the length of the glass, alternating in adjacent strips for the entire length. This device is called a compound quarter-wave plate, and when circularly polarized light passes thru the mica, it is changed to plane polarized light (due to the retardation by a quarter of a wave) and is transmitted by the Nicol prism if the vibrations are parallel to the length of the prism, or extinguished if at right angles to it.

When a spot near the center of the Sun is examined we find certain lines in the spectrum widened, and others resolved into two or three components. This effect is due to the magnetic field produced by the ionized particles that emit the light, whirling in a vortex[1] and producing the same effect as an electric current flowing in a coil of wire, which is a magnet.

When a source of light between the poles of a magnet is examined with a spectroscope, most of the spectrum lines are seen to be broken up into three or more components. If examined along the lines of force, the side components are found to be circularly polarized with opposite sign, e. g., red component +, violet component −, or vice versa; and if a compound quarter-wave plate, as described above, is used, we see the red and violet components thru alternate strips.

Now if we examine the spectrum of the spot referred to above by passing the light thru the analyzer, we will see certain of the lines in the spectrum zigzagging on alternate strips, showing the presence of circularly polarized light in sun-spots. Some lines are affected much more than others, and the iron line at λ 6173.553 is especially suited to the examination and measurement of magnetic field strength.

This separation of the components of the lines is measured by means of a parallel plate micrometer. The micrometer consists of a piece of one-eighth-inch plate glass mounted so that it can be rotated about an axis lying in its plane, and at right angles to the edge, which is placed so that it falls on or touches the image of the

[1]See Hale's "Notes on Solar Magnetic Fields and Related Phenomena," *these Publications*, **22**, 63, 1910.

PLATE III

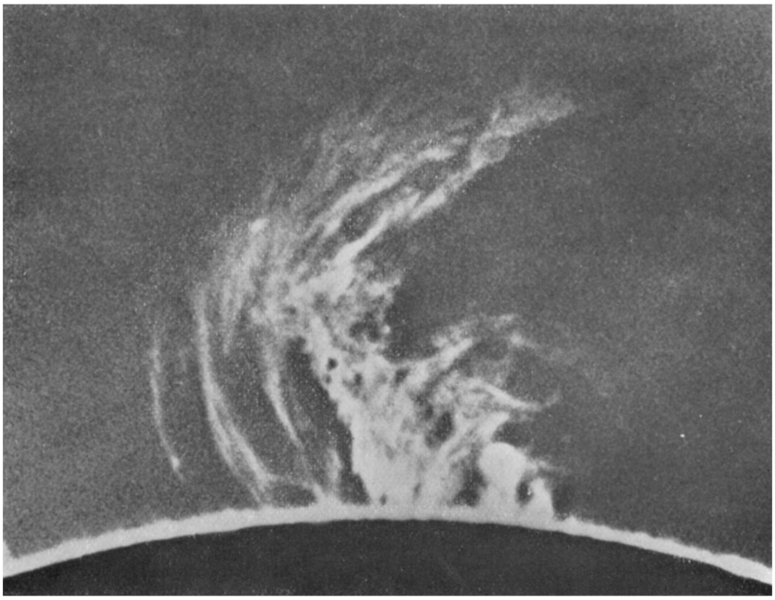


FIG. 1. A ›rominence 140,000 miles high, photographed with the K line of calcium on July 9, 1917.

a b c d

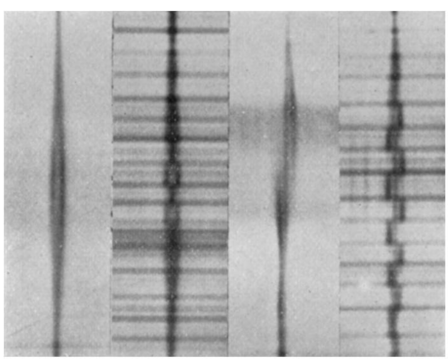


FIG. 2. Iron triplet λ 6173.553 in spectra of sun-spots. a and b, plane polarized light of spot near the Sun's limb, taken with Nicol and (a = single, b = compound) half-wave plate; c and d, circularly polarized light of spot near center of the Sun, taken with Nicol and (c = single, d = compound) quarter-wave plate; c shows reversal of sign of charge of two adjacent umbrae of large spot group of August, 1917.

junction between two mica strips, as seen in the spectrum by means of a low-power lens mounted above the plate glass. The glass is turned thru an angle sufficient to bring the component of the line viewed thru the glass into coincidence with the component on the adjacent strip, and a notation is then made on the spot sketch of the reading of the angle, recording also whether the red or the violet component of the line is transmitted by a certain marked strip, which is always used for reference. The field strength is obtained by means of a conversion curve or table.

When light from a source in a magnetic field is viewed across the lines of force, the components of the line are plane polarized, the light emitting the side components vibrating in a direction inclined 90° to that of the light giving the middle component. In this case the quarter-wave plate used as above for circularly polarized light must be supplanted by a half-wave plate. This is done by placing a single strip of quarter-wave mica over the compound quarter-wave plate, in such a way that the light transmitted is plane polarized parallel to and at right angles to the Nicol prism. If we now examine a triplet with this combination we will see alternately the side and central components of the line.

When the sun-spot near the edge of the Sun is examined we are receiving the light across the lines of force and the light is plane polarized, and if a triplet is examined with the compound half-wave plate and Nicol prism, the appearance of the spectrum line is similar to that of an ordinary link chain, the side and middle components alternating on the mica strips.

In Plate III, Fig. 2, is illustrated the appearance of the iron line λ 6173.553 under four different conditions. In each case the Nicol prism is used, and from a spot near the Sun's limb plane polarized light is received and examined in (a) with a single half-wave plate and in (b) with a compound half-wave plate. (c) and (d) are of spots near the Sun's center, giving circularly polarized light, (c) with single quarter-wave plate and (d) with compound quarter-wave plate. In (c), two umbrae of the great spot group of August, 1917, had opposite signs of charge and caused the side components of the line to alternate from one side to the other as one follows the length of the line. If the spots had been of the same sign or polarity, the side components would have remained on one side of the middle component.

The field strength of a spot varies approximately in proportion to the size of the umbra, and regardless of the size of the group. Average spots range from 2000 to 2700 gausses, while some of the largest have shown as high as 4000 gausses when using the iron line λ 6173.553 which for 10,000 gausses gives a separation of 0.84 A.

Photographic records are made of portions of the spectra of the larger spots and all the lines are subsequently measured. Spectra made with the compound quarter-wave plate and Nicol prism have been secured of a number of large spots, suitable for preparing a map of the sun-spot spectrum, from λ 3800 to λ 6600. The region λ 6000 to λ 6450 is complete, and it is hoped the remainder can be prepared during the present winter. The scale of the map is 10^{mm} per A, and 50 A per sheet, with a few units of overlap.

The general magnetic field of the Sun has received a large amount of attention and preliminary results were published[1] in 1913. During the summer of 1914 a series of daily spectra, covering several months with hardly an interruption, were secured from which material a thoro investigation has been made and a discussion of some of the results published in the *Astrophysical Journal*, **47**, 206, 1918. The observed latitude of maximum displacement is very close to the theoretical latitude of 45°, north and south, and varies with different elements and lines, which in a way represent levels. The values range from 10 to 60 gausses. There appears to be an inclination of the magnetic axis to the axis of rotation of several degrees, and a rotation period of about thirty-two days is indicated by the results. The obtaining of further material will have to be deferred until the spot period approaches the minimum, so as to avoid the local disturbing influence of sun-spot regions.

The motions of the vapors of various elements in the spots have been studied and results published by St. John.[2] He shows that the vapors of iron and heavier elements are flowing outward from the spots; aluminum lines, some magnesium lines, and calcium λ4227 are produced near the level of inversion, and Hδ, D1 D2, magnesium b1 b2, Hγ, H2 K2, Hα, and H3 K3 show increasing velocities towards the spots in the order mentioned.

The study of the solar rotation by means of spectral line displacement is still in progress, and some interesting facts are coming

[1]Hale, *Astrophysical Journal*, **38**, 27, 1913.
[2]St. John, *Astrophysical Journal*, **38**, 341, 1913.

out of it. The rotation period as determined from different lines, varies, not only for different elements, but also for different lines of the same element, indicating a different period for different levels. See St. John, in the December number of this journal.

The spectra for determining solar rotation are made by bringing the light from opposite limbs of the Sun on to the slit of the spectrograph by means of prisms. Over the slit are mounted three prisms, two receiving light from one limb, and the third, placed between the first two, receiving light from the opposite limb. Two auxiliary prisms mounted on slides bring the light from the Sun's edge to the prisms over the slit. Three narrow spectra are thus obtained close together on a single plate. Two sections of such a plate are reproduced in the February, 1918, number of this journal; they show very well the displacement of the solar lines in the middle spectrum towards the violet, compared with the top and bottom, indicating an approaching source, and therefore representing the light from the east limb. Note also the non-shifting of the lines of the great B group, which are of terrestrial atmospheric origin.

When conditions of good definition and other work permit, visual observations of the hydrogen Hα line are made around active sun-spot groups, for observing the distortions due to radial velocity, and for reversals of the line over the bright hydrogen regions. When unusual phenomena present themselves, photographic records are made. In the region of the great sun-spot group of August, 1917, distortions of the Hα line, indicating a falling back toward the Sun of 150^{km} per second, were recorded, and, when the group was at the limb, the chromosphere was greatly disturbed and many interesting photographs of Hα were secured. It is hoped that some of these may be shown in a later note.

It was while observing the Hα line over a spot group in September, 1915, that a phenomenon[1] was discovered by the writer which had previously escaped our attention. Around the edge of the penumbra or between spots in an active group, there are frequently very small areas where the Hα line shows a bright band running at right angles to the line, extending usually 4 or 5 A on each side, lasting for a few minutes only, and then rapidly fading away. Sometimes several of these phenomena follow one another at intervals varying

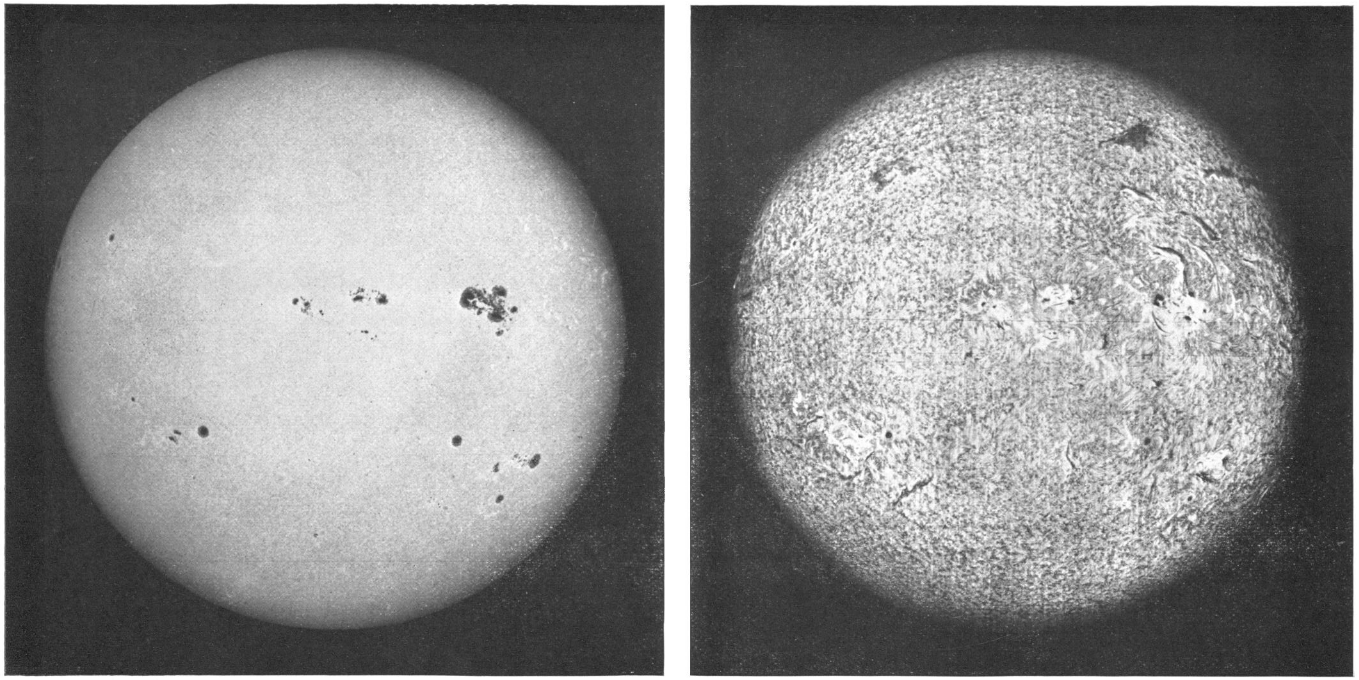
[1]Ellerman, *Astrophysical Journal*, **46**, 298, 1917.

from a few minutes to half an hour. They occur only around active groups and are no doubt of an eruptive character, but deep seated, probably below or in the photosphere, as there is no effect on the absorption line, as would happen if the phenomena originated at the level of the bright structure which the hydrogen spectroheliograms show.

The very diminutive size, combined with the sudden appearance and disappearance, has suggested the name of hydrogen bombs. The phenomenon is visible only in the hydrogen lines. The $H\beta$ line shows it to a less pronounced degree than $H\alpha$, and in $H\gamma$ only a feeble band is seen. No other lines in the spectrum seem to be affected.

The foregoing account outlines in brief some of the solar researches in progress at this observatory at the present time.

PLATE I



Photoheliogram and hydrogen ($H\alpha$) Spectroheliogram of the Sun, made on August 12, 1917.